ARL 72-0025
MARCH 1972

Aerospace Research Laboratories

HEA TRANSFER AND ATTRITION
PROCESSES AT THE ANODE
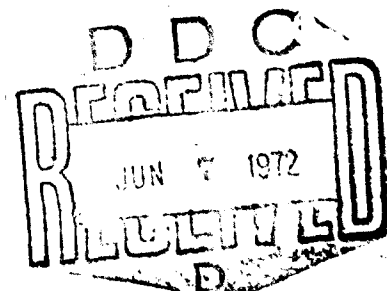# OF PULSED HIGH INTENSITY ARCS

J. L. SMITH
E. PFENDER
E. R. G. ECKERT

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINNESOTA

Details of illustrations in
this document may be better
studied on microfiche

D D C

JUN 7 1972

AIR FORCE SYSTEMS COMMAND
United States Air Force

53

ARL 72-0025

HEAT TRANSFER AND ATTRITION PROCESSES AT THE ANODE OF PULSED HIGH INTENSITY ARCS

J. L. SMITH, L. ENDER, AND E. R. G. ECKERT

HEAT TRANSFER DIVISION
DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF MINNESOTA
MINNEAPOLIS, MINNESOTA

MARCH, 1972

I

FOREWORD

This final report was prepared by the Department of Mechanical Engineering, University of Minnesota, and covers work performed during the period from June 16, 1970, to December 15, 1971, under Contract F 33615-70-C-1668 for the Aerospace Research Laboratories, Air Force Systems Command, USAF. The actually funded contracting period was from June 16, 1970, to June 15, 1971.

The research reported herein was accomplished on Project 7063 under the technical cognizance of Mr. K. R. Cramer of the Thermomechanics Research Laboratory, ARL.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
University of Minnesota Department of Mechanical Engineering Minneapolis, Minnesota 55445	UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

Heat Transfer and Attrition Processes at the Anode of Pulsed High Intensity Arcs

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific - Final

5. AUTHORS (First name, middle initial, last name)

J.L. Smith
E. Pfender
E.R.G. Eckert

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1972	50	12

8a. CONTRACT OR GRANT NO. F33615-70-C-1668	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 7063-00-13	
c. DoD Element 61102F	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d. DoD Subelement 681307	ARL 72-0025

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
TECH OTHER	Aerospace Research Laboratories (LV) Wright-Patterson AFB, Ohio 45433

13. ABSTRACT Tests of a high current pulsed arc with the intent to investigate anode erosion characteristics are described. The range of arc parameters covers currents from 5000 to 10,000 amps (square pulse) with time intervals from 20×10^{-6} to 200×10^{-6} seconds. The arc is designed to be stationary; i.e., there are no external magnetic fields and the arc configuration produces self-magnetic fields which are symmetric so as not to move it. It is found, however, that with any but flat electrodes there is an inherent self-magnetic field which will move the attachment points for sufficiently high currents. Spectrometric investigations reveal that there is no anode vaporization for the range of parameters investigated. Rather liquid metal is generated and blown by the action of cathode jet in a radial direction maintaining a relatively cool surface. The cathode, on the other hand, vaporizes in a matter of a few tens of a microsecond for an arc of a few hundred amps. A computer program is described for solving the one-dimensional problem of a constant heat flux impinging on a surface of a material with temperature dependent properties with a liquid-solid interface penetrating the material.

DD FORM 1473 (1 NOV 65)

Electrode Attrition
Anode
Arcs
Pulsed

B

B

ABSTRACT

Tests of a high current pulsed arc with the intent to investigate anode erosion characteristics are described.

The range of arc parameters covers currents from 5000 to 10,000 amps (square pulse) with time intervals from 20×10^{-6} to 200×10^{-6} seconds.

The arc is designed to be stationary; i.e., there are no external magnetic fields and the arc configuration produces self-magnetic fields which are symmetric so as not to move it. It is found, however, that with any but flat electrodes there is an inherent self-magnetic field which will move the attachment points for sufficiently high currents.

Spectrometric investigations reveal that there is no anode vaporization for the range of parameters investigated. Rather liquid metal is generated and blown by the action of cathode jet in a radial direction maintaining a relatively cool surface.

The cathode, on the other hand, vaporizes in a matter of a few tens of a microsecond for an arc of a few hundred amps.

A computer program is described for solving the one-dimensional problem of a constant heat flux impinging on a surface of a material with temperature dependent properties with a liquid-solid interface penetrating the material.

iii

TABLE OF CONTENTS

NOMENCLATURE

a = Arbitrary constant

C = Capacitance

c = Specific heat

B = $\Delta\tau/(\Delta x)^2$

CHI = Non-dimensional quantity indicating heat flux, Eq. 10

E = Internal energy (energy units/unit volume)

f_1 = Function defined by Eq. 6c

f_2 = Function defined by Eq. 6a

H = Front face heat flux

H_f = Latent heat of fusion

I = Current

K = Thermal conductivity

L = Inductance

N = Number of elements in Guillemin network

T = Temperature

T_M = $T_m - T_{Ambient}$

U = Capacitor charging voltage

u = Non-dimensional temperature, Eq. 3

w = Non-dimensional temperature, corresponds to u, but a solution to the finite difference equation

x = Real space variable

Z = Impedance

z = Non-dimensional space variable, Eq. 7a

ϕ = Function defined by Eq. 6e

β = Coefficient chosen for Eq. 6a

$\triangleq$ = Equal by definition

δ = Transmission line transit time

γ = Fraction of first phase

ρ = Density

τ = Non-dimensional time, Eq. 2

λ = Constant defined by Eq. 6d

Subscripts

Amb = Ambient

f = Subscript on H, latent heat of fusion

i = Refers to space step

k = Refers to time step

M = Used only for $T_M = T_m - T_{Amb}$

m = Refers to value of variable at the melting point

o = Properties at temperatures at which K_o and c_o are chosen, see Eq. 6b

V = Vaporization

LIST OF ILLUSTRATIONS

I. INTRODUCTION

Although electric arcs and transient discharges have been
known for many decades, their electrode regimes are still poorly
understood. There is, for example, even for steady arcs no
consistent quantitative theory of the anode region available
which would permit a complete interpretation of the observed
anode phenomena.

The physical dimensions of and the extreme conditions in the
anode region of high intensity discharges prohibit the application
of many conventional diagnostic tools. In addition to the usual
problems of probing the fall spaces without disturbing the plasma,
one finds severe problems associated with unavoidable erosion
as steady state conditions are approached. Measurements in
transient discharges of short duration require careful shielding
of the electrical circuits in order to reduce the extremely high
noise levels superimposed to electric signals.

Any improvement of existing plasma devices, as for example,
arc gas heaters, plasma torches for welding, cutting, and spraying,
as well as new developments require, however, a thorough under-
standing of the electrode regions because excessive electrode
attrition represents the limiting factor for the lifetime of such
devices.

Although numerous attempts have been made to improve our
understanding of the electrode regions, available results are
frequently concerned only with phenomenological observations and

the interpretation of the results sometimes leads to contradicting conclusions. Since electrode attrition can be reduced by continuously moving the electrode attachments, magnetically driven arcs attracted increasing interest. It is, however, difficult to gain a fundamental understanding of the electrode regions from such experiments because of the unknown effects of the magnetic field on the electrode regions.

The electrode regions of stationary arcs have been studied by a number of investigators (12, 14, 15). Most of them, however, are only concerned with data for a particular application which contribute little to a fundamental understanding.

In order to arrive at conclusions of general validity, undesirable side effects have to be eliminated. A striking example of such a side effect is the cathode jet impinging on the anode surface at the location of the anode arc attachment. The observed anode erosion pattern changes drastically if the influence of the cathode jet is eliminated.

The objective of this study is a quantitative assessment of the heat transfer to and the associated attrition of the anode in a pulsed high intensity arc. The establishment of well defined and reproducible conditions at the anode is a prerequisite for meaningful data and. therefore, this aspect is particularly emphasized.

II. ANALYTICAL CONSIDERATIONS

Concepts

One can think of the following sequence of events in the anode when the arc is struck: First, the surface begins to heat up and a temperature profile is established according to the conduction equation for a surface heat flux (neglecting Joule heating) until the surface reaches the melting temperature, at which point a liquid-solid interface begins to penetrate the anode as the surface temperature continues to rise until the surface reaches the vaporization temperature.

The assumptions in the above picture are that Joule heating is negligible with respect to the surface heat flux and that the liquid layer is stationary. The first assumption is considered by Ref. 13. Ref. 14 did an experimental work which essentially investigated this question and concluded volumetric heating does occur in the anode. However, for the same arc it was concluded that volumetric heating did not occur at the cathode. This is obviously self-contradictory, as it is well accepted that the current density is higher at the cathode than at the anode so that, if the current density at the anode is sufficient to cause appreciable Joule heating, there will most certainly also be Joule heating at the cathode. It is much more likely that, as will be discussed later, the anode heats relatively slowly and consequently builds up a relatively thick liquid layer which is then blown out by the cathode jet. Thus, the second critical assumption that the

3

liquid layer is stationary for this model comes into play. This
assumption will likely be good as long as one can eliminate the
cathode jet impingement onto the anode surface which, of course,
one must do if one is truly to look at anode phenomena. Also, the
surface must reach vaporization relatively quickly.

Exactly what relatively quickly is depends on the gas pressures
to which the liquid layer is exposed. If the inertia of the
material holds it essentially stationary in the time it takes to
reach vaporization, then the assumption is good. A priori this
seems most likely. If, on the other hand, gas pressure is sufficient
to move the liquid layer almost instantaneously, then the model
would have to be changed to the assumption that the liquid layer
is removed as soon as it is formed and then the heat flux would
be deduced from the time to the onset of erosion and/or the depth
of the erosion pit for a given duration arc. Which of these is
the best assumption cannot be said before the experiment is actually
performed. Because the times involved are short and there is no
anticipated source of high gas velocities, assuming that the cathode
jet influence is removed, one would expect the former to be best.
However, the heat flux can be only estimated to within about two
orders of magnitude (discussion following Ref. 12 and Fig. 5) and
the phenomena in the fall regions are not completely understood,
so one cannot say with certainty that the liquid will remain
stationary.

Basic Equations

General Problem:

This really represents two problems in one; the first being conduction in a solid, and the second being conduction through a liquid, through a moving liquid solid boundary, then through a solid.

The first part is governed by the equation

$$\frac{\partial T_2}{\partial t} = \alpha_2 \frac{\partial^2 T_2}{\partial x^2}$$

with boundary conditions

$$Q(x=0) = H = Const$$

$$\lim_{x \to \infty} \frac{\partial T_2(t,x)}{\partial x} = 0$$

$$\lim_{x \to \infty} T_2(t,x) = T_{Amb}$$

and initial condition

$$T(0,x) = T_{Amb}$$

The second part may be represented by the following equations:

Liquid Region
$$\frac{\partial T_1}{\partial t} = \alpha_1 \frac{\partial^2 T_1}{\partial x^2}$$

Solid Region
$$\frac{\partial T_2}{\partial t} = \alpha_2 \frac{\partial^2 T_2}{\partial x^2}$$

Solid-Liquid Interface
$$\rho H_f \frac{dX(t)}{dt} = K_1 \frac{\partial T_1}{\partial x} - K_2 \frac{\partial T_2}{\partial x}$$

The following boundary conditions apply to these equations:

$$X(0) = 0$$

$$T_1(t,X(t)) = T_2(t,X(t)) = T_m$$

$$\lim_{x \to \infty} \frac{\partial T_2(t,x)}{\partial x} = 0$$

$$\lim_{x \to \infty} T_2(t,x) = T_{Amb}$$

$T_2(0,x)$ = solution to first problem when the surface reaches the melting temperature

Constant Property Solution:

When material properties are assumed to be independent of temperature, the solution is considerably simplified. The first part of the problem has an analytic solution (Ref. 9).
The time required for the surface to reach melting is

$$t_m = \frac{\pi (T_M)^2 K_2 \rho c_2}{4H^2}$$

6

with a corresponding temperature profile of

$$T - T_{Amb} = T_M \exp\left(\frac{-x^2 H^2}{T_M^2 K_2^2 \pi}\right) - \frac{hx}{K_2} \text{erfc} \left(\frac{xH}{T_M K_2 \sqrt{\pi}}\right)$$

The second part of the problem is exactly as previously stated except that $T_2(0,x)$ is known. This is one of the many variations of the "Stefan Problem" which has no analytic solution. It is, however, amenable to an analog computer solution and has been solved for a number of metals by Cohen (Ref. 1).

Unfortunately, the constant property assumption is not a good one for most materials.

Variable Property Solution:

The moving boundary between the solid and liquid regimes presents a considerable complication as compared to a single phase conduction problem. However, a clever way of circumventing this problem has been developed by Hashemi and Sliepcevich (Ref. 2). Essentially it consists of assuming that melting occurs over a small but finite temperature range, rather than at a particular temperature. This assumption allows one to consider the melting problem as a conduction problem of a single phase with variable properties, as will be seen.

This approximation may be thought of in the following manner. If the material in question melts at a single temperature, the latent heat of fusion can be looked at as an impulse function in the specific heat located at the melting temperature. We

7

assume this spike is not infinitely narrow but is a pulse of finite width.

If the material is not pure, this assumption is probably more nearly an accurate model of the real situation than would be a single melting point. It provides a very convenient means of accounting for phase transitions which occur in materials such as iron. Phase transitions in these materials appear as fairly wide pulses in the specific heat curves.

The heat conduction equation may be written as

$$\frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) = \rho \left(\frac{1}{\rho} \left(\frac{\partial E}{\partial T} \right)_\rho \right) \frac{\partial T}{\partial t} \tag{1}$$

Note that specific heat is not used, but rather $\frac{1}{\rho} \left(\frac{\partial E}{\partial T} \right)_\rho$ in anticipation of the use of a fictional specific heat which includes the latent heat of fusion.

Define

$$\tau \triangleq (t/a^2) \, (H^2/T_M^2 K_0 \rho c_0) \tag{2}$$

$$u \triangleq \int_{T_{Amb}}^{T} K dT \Big/ \int_{T_{Amb}}^{T_V} K dT \tag{3}$$

which transforms Equation (1) to

$$\frac{\partial^2 u}{\partial x^2} = \frac{\rho}{K} \left(\frac{1}{\rho} \left(\frac{\partial E}{\partial T} \right)_\rho \right) \frac{\partial(u)}{\partial \tau} \, (H^2/a^2 T_M^2 K_0 \rho c_0) \tag{4}$$

8

Using the procedure of Ref. 2,

$$\frac{1}{\rho} \frac{\partial E}{\partial T})_\rho = c(T) + H_f \left(\frac{\partial \gamma}{\partial T}\right)_\rho$$

$$= c(T) + H_f \left(\frac{\partial \gamma}{\partial u}\right)_\rho - \frac{K(T)}{\int_{T_{Amb}}^{T_V} K dT} \tag{5}$$

Equation (4) then becomes

$$\frac{\partial^2 u}{\partial x^2} = \left(\frac{H}{a T_M K_o}\right)^2 \left(\frac{K_o c(u)}{c_o K(u)} + \frac{K_o H_f \left(\frac{\partial \gamma}{\partial u}\right)_\rho}{c_o \int_{T_{Amb}}^{T_V} K dT}\right) \frac{\partial u}{\partial \tau} \tag{6}$$

The following definitions and assumptions are made

$$\frac{\partial \gamma}{\partial u})_\rho = \frac{\beta}{\sqrt{\pi}} e^{-\beta^2 (u_m - u)^2} \triangleq f_2(u) \tag{6a}$$

Note that as $\beta \to \infty$, f_2 becomes an impulse function at (u_m). Also note that $\int_{-\infty}^{\infty} f_2(u) du = 1.0$.

Choose u_o such that

$$K_o/c_o = Max_{0 \leq u \leq 1} (K(u)/c(u)) \tag{6b}$$

$$f_1(u) \triangleq \frac{K_o/c_o}{K(u)/c(u)} - 1.0 \tag{6c}$$

$$\lambda \triangleq H_f / (c_o \int_{T_{Amb}}^{T_V} K(T)/K_o \, dT) \tag{6d}$$

9

$$\phi(u) = 1 + f_1(u) + \lambda f_2(u) \tag{6e}$$

With these applied to Equation (6), it becomes

$$\frac{\partial^2 u}{\partial x^2} = \phi(u) \frac{\partial u}{\partial \tau} \left(\frac{H}{aT_M K_0}\right)^2 \tag{7}$$

Define

$$z \triangleq H x/aT_M K_0 \Big| \qquad \text{Then Equation (7) becomes} \tag{7a}$$

$$\frac{\partial^2 u}{\partial z^2} = \phi(u) \frac{\partial u}{\partial \tau} \tag{8}$$

The function $\phi(u)$ can be evaluated from a knowledge of material properties.

Using the Crank-Nicholson method, the finite difference form of Equation (8) becomes

$$\phi(w_{i,k+1/2}) \left(\frac{w_{i,k+1} - w_{i,k}}{\Delta \tau}\right) =$$

$$= \frac{(w_{i-1,k} - 2 w_{i,k} + w_{i+1,k}) + (w_{i-1,k+1} - 2 w_{i,k+1} + w_{i+1,k+1})}{2 (\Delta z)^2}$$

where

    i refers to position

    k refers to time

    w is used to denote the solution to the finite difference equation, corresponding to u which is the solution to the differential equation

Since Δz contains an arbitrary scale factor, we can set

$$\Delta z = 1 \text{ and}$$

$$\Delta \tau / (\Delta z)^2 = B$$

The stability of this equation has been considered (Ref. 3)
with the conclusion that it is unconditionally stable. However,
it was considered for ϕ evaluated at the kth node rather than
(k+1/2). Douglas (Ref. 4) recommends evaluation at node (k+1/2)
for a general form of Equation (2); it is suggested to evaluate
ϕ at (k+1/2) by an iterative procedure, a backward difference
method, or an extrapolation from previous times. The first two
of these would cost computer time so the latter is preferable
if feasible. In the solution for copper, it was found to matter
little whether $\phi(i,k)$ or $\phi(i,k+1/2)$ was used. The equations
were first solved using $\phi(i,k)$ and the solution examined to see
the feasibility of predicting $w(i,k+1/2)$ from $w(i,k)$ and $w(i,k-1)$.
It was found that except initially at the front face, a linear
extrapolation would come quite close. Further, the function ϕ
was fortuitously close to constant at low values of w so that
where the linear extrapolation was not valid the error was small.

The boundary conditions to be used in conjunction with
Equation (9) in order to obtain the solution are

Front face:

$$H = -K \left(\frac{\partial T}{\partial x} \right)_{x=0} = -\int_{T_{Amb}}^{T_V} K d\bar{T} \left(\frac{\partial u}{\partial x} \right)_{x=0}$$

$$\frac{w_{1,k} - w_{2,k}}{\Delta x} = H / \int_{T_{Amb}}^{T_V} K dT$$

This may be written in terms of (Δz) and recalling that $\Delta z = 1.0$

$$w_{1,k} - w_{2,k} = \frac{aK_o T_M}{\int_{T_{Amb}}^{T_V} K dT} \triangleq CHI \qquad (10)$$

Rear conditions:

$$\left.\frac{\partial u}{\partial x}\right)_{x \to \infty} = 0$$

$$w_{I,k} - w_{I-1,k} = 0 \qquad \text{for all } k$$

These Equations (4, 5, 6) may be represented in the following matrix form

$$
\begin{bmatrix}
-1 & 1 & 0 & 0 & & & & \\
1 & -2(\frac{\phi_{2,k}}{B}+1) & 1 & 0 & & & & \\
0 & 1 & -2(\frac{\phi_{3,k}}{B}+1) & 1 & & & & \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \\
\cdot & \cdot & \cdot & \cdot & & & & \\
& & & \cdot & 1 & 0 & & \\
& & \cdot & \cdot & \cdot & 1 & -2(\frac{\phi_{I-1,k}}{B}+1) & 1 \\
& & \cdot & \cdot & \cdot & 0 & 1 & -1
\end{bmatrix}
\begin{bmatrix}
w_{1,k+1} \\
w_{2,k+1} \\
\cdot \\
\cdot \\
\cdot \\
\cdot \\
\cdot \\
\\
w_{I,k+1}
\end{bmatrix}
=
$$

$$
\begin{bmatrix}
\text{CHI} \\[6pt]
w_{1,k} + 2\left(\dfrac{\phi_{2,k}}{B} - 1\right) w_{2,k} + w_{3,k} \\[10pt]
w_{2,k} + 2\left(\dfrac{\phi_{3,k}}{B} - 1\right) w_{3,k} + w_{4,k} \\[10pt]
\cdot \\
= - \qquad \cdot \\
\cdot \\[10pt]
w_{I-2,k} + 2\left(\dfrac{\phi_{I-1,k}}{B} - 1\right) w_{I-1,k} + w_{I,k} \\[10pt]
0
\end{bmatrix}
\qquad \text{for all } k
$$

In this form, it may be solved successively for each time interval if an initial temperature profile is assumed.

Note that this transformation of variables results in complete elimination of heat flux from the equations. This permits one solution to be applied to any heat flux just as long as the one-dimensional criterion is met.

Equations as applied to the solution for copper

The thermal conductivity for copper was taken from Ref. 6. Separate polonomials were fit to the curves for the liquid region and for solid region from which u was calculated (Fig. 1, 2, and 3). The specific heat was taken from Ref. 5. A polynomial in u was fit to the curve of $\frac{C}{K}$ versus u as calculated from these properties. From this, an equation for f_1 was obtained. To

obtain the value of f_2 (u), a value of $\beta = 30$ was taken and u_m set at the value corresponding to the melting temperature was taken. This gives a ϕ as shown in Fig. 4. In this figure, the actual and assumed curves for ϕ are shown. The actual curve would have an impulse function at u = 0.5988 (melting point of copper) whereas the assumed curve has the spike shown.

The results of the computer program are shown in Fig. 5. Note that the time to vaporization is considerably less than calculated by Cohen [1]. This is very reasonable as the value of the thermal conductivity is much lower in the liquid region than in the solid region. Cohen's calculation used a constant conductivity value equal to the value at room temperature.

III. EXPERIMENTS

A. Apparatus

Current Source

A Guillemin line with a matched load and low inductance leads to the test chamber provides a square current pulse of variable duration and magnitude. The Guillemin network is a lumped parameter simulation of a transmission line. As the number of elements increases, it becomes quite a close approximation to a transmission line and all results of transmission line theory are applicable. The basic properties of such a network are examined in Ref. 10 and 11.

The output impedance must be matched to the L-C network according to

$$Z_0 = \sqrt{L/C}$$

If this is the case, the pulse will be square of amplitude

$$I = U/2\ Z_0 \quad \text{(See Fig. 7a)}$$

The pulse duration is twice the transit time for the simulated transmission line.

$$\text{i.e.,} \quad \tau = 2\delta = 2N\ \sqrt{CL}$$

It turns out that the results shown in Fig. 7b and 7c are extremely important for this application. Note particularly

that in Fig. 7c, characteristic of an undersized output
impedance, the circuit has a tendency toward a damped oscillatory
current in the load. This, as will be discussed later, is a
critical point to observe.

Test Chamber and Electrodes

The chamber in which the electrodes are housed is constructed
of a 12-inch diameter by 9-inch high by 1-inch thick aluminum
cylinder. There are two 5-inch diameter windows located midway
vertically and directly opposite each other. A vacuum connection
is provided at 90° to each window.

The main electrical leads are through the bottom of the
chamber. The anode is located below the cathode, and its connection
comes directly up through the center of the lower cover (Fig. 8).
The cathode, located on the axis of the chamber above the cathode,
is mounted in a symmetric manner on two posts from the bottom of
the chamber.

The anode samples are in the shape of 1 1/4" x 1 1/4" x 1/4"
pieces. These slip into a tapered mount which provides good
electrical contact as well as expedient insertion and removal.

The cathode configuration, generally found to be of
significant influence on the anode, will be discussed extensively
later.

Matching Resistance/Low Inductance Leads

It is important that, if the ideal characteristic current
of Fig. 7a is to be achieved, the output impedance be nearly a

16

pure resistance. If there is appreciable inductance, the pulse rise time will be slowed. To avoid this, the connection from the Guillemin network is made via a line made of two 4-inch x .001-inch stainless strips separated by .003-inch mylar and clamped together.

The capacitor bank is housed in a specially constructed cabinet 7 ft. long x 4 ft. high x 3 ft. deep. The connections to the bank exit from one end.

This provides a rise time essentially limited only by the L-C values of the Guillemin network.

Circuit

There are two basic circuits which have been used. At times a cathode was used which had a sparker to ignite the arc (Fig. 9), whereas in later experiments it was found that the cathode was influencing the anode so cathodes without sparkers were used (Fig. 10).

Spectrometer and Instrumentation

A Jarrel Ash Model 82-020 spectrometer is used with an RCA IP28 photomultiplier with a special dynode chain and mount to provide a signal to a Tektronix 555 dual beam oscilloscope. The current shunt and the photomultiplier outputs are simultaneously displayed which provides a time reference for the photomultiplier output.

B. Experimental Procedure

Two Guillemin networks have been used; the first was a
40 section line of 1/2 micro-farad capacitors and 1/2 micro-
Henry inductors which provided a 40 microsecond pulse of up to
5000 amp and the second a 50 section line of 2 micro-farad capacitors
which provides either a 200 microsecond pulse of up to 5000 amps
with 2 micro-Henry inductors or a 100 microsecond pulse of up
to 10,000 amps with 1/2 micro-Henry inductors. The smaller
network used a Signalite spark gap and the larger, a Westinghouse
7703 Ignitron as a switch.

Initial Work

Early experiments used the smaller of the two lines. A
hollow cathode with a coaxial sparker was used in these experiments.
This apparatus was essentially identical to that used by earlier
experiments (Ref. 13). It did not, however, exhibit the same
erosion characteristics. Use of the spectrometer provided the
answer to this dilemma. Fig. 11 shows a typical spectrometer
output when the spectrometer is adjusted to a strong line of the
anode material. The second sharp high amplitude rise in the
photomultiplier output is seen only when on an anode material
line and is explainable on the basis of behavior of the pulse
forming network. Earlier it was pointed out that the characteristics
demonstrated in Fig. 7 would play an important part in the analysis
of the experiments. Note that if the output resistance is too
small, the initial current pulse is larger. Thus being naturally

18

inclined to get the most out of a given piece of equipment, the experimenter will tend to install the smallest resistance value that seems reasonable. He decides the value to use by looking at the shunt output. When the overshoot appears to be becoming excessive, the resistance value is made no smaller. Due to the scales involved, in order to see the first pulse of several thousand amps, one does not see this overshoot until it reaches at least the order of 100 amps'. Unfortunately any overshoot at all is excessive. The anode becomes the cathode during the period of this reverse current. The cathode heating is extremely localized and results in very rapid erosion, which is the explanation of the second rise in spectrometer output of Fig. 11. Cathode, rather than anode, material is being vaporized.

It is obvious that one must build the apparatus with a tendency toward too high a resistance value so that the current shown in Fig. 7b is realized. Note that it is impossible to attain the idealized case of Fig. 7a since the arc does not constitute a constant impedance and also we are using a lumped parameter approximation to a transmission line.

With this potential pitfall recognized and with slightly excessive resistance, it was found that not only could copper vapor not be detected by the spectrometer, but no erosion could be detected either. There was only a fairly large discolored area. It was concluded that the pulse duration was not sufficient to cause erosion. As will be discussed later, this is not the

entire problem; there is also an effect due to cathode induced
arc motion.

Larger bank with coaxial sparker cathode

The larger capacitors were purchased and an entirely new
apparatus was built. This was set up initially with 2 micro-Henry
inductances so as to get a 200 microsecond arc of 5000 amps in a
1 Ohm resistance when the capacitor bank was charged to 10,000
volts. This pulse forming network required an Ignitron to switch
it as the capabilities of the previously used spark gap were
exceeded. With the exception of the Ignitron trigger circuit,
heater, etc., the circuit was essentially the same as was previously
used. The same coaxial cathode sparker was used.

After considerable work with this apparatus, it was found
from the spectrometer output that there was no anode material
appearing in the arc. What is more, the anode surface appearance
was very similar, though more discolored, to its appearance for
the 40 microsecond, 5000 amp arc.

It appeared that there was still not enough energy to cause
erosion.

The possibility of reducing the inductances to 1/2 micro-Henry
so as to get a 100 microsecond pulse of 10,000 amps in a 1/2 Ohm
resistance when the capacitor bank was charged to 10,000 volts
was considered. This method of increasing current is very limited
for one must also decrease the matching resistance according to
$Z_o = \sqrt{L/C}$. In order to get anything approaching a square pulse,

the line resistance must be much greater than the widely varying arc impedance. If the anode spot size and the anode fall were to remain roughly constant when the current doubled, one would expect the heat flux to double; at least one would expect a considerable increase. Calculations show (Fig. 5) that the time to vaporization is inversely proportional to the square of the heat flux. This is true for either the constant or variable property calculation. Thus, if the heat flux were doubled, the time required to vaporize the anode material would be cut by four, whereas the pulse duration would be cut by two. Thus, it was decided to try a 10,000 amp, 100 microsecond arc.

The apparatus was modified to do this. The result was much the same as for the 5000 amp, 200 microsecond arc.

Larger bank, effect of cathode configuration

During the tests with the cathode with the coaxial sparker (Fig. 12) at 10,000 amps, it was noted that the entire tungsten tip had a velvety appearance. As this cathode had been recently rebuilt, it was evident that the cathode attachment was moving extremely rapidly over the whole cathode tip. This is extremely important because of the cathode jet. When the jet emanates from the side of the cathode, it most certainly tends to cause the anode attachment area to move away from directly under the cathode in this direction. In all likelihood, the rapidly moving cathode attachment induces a rapid motion of the anode attachment within a radius centered directly below the cathode. This, of course,

would reduce the time averaged heat flux to an extremely low level. This explains the results of the experiments thus far described. This sort of motion for this cathode design is seen in the photographs in Fig. 3 of Ref. 15.

It was decided to try a pointed solid tungsten cathode (Fig. 13), the type cathode usually used in the High Temperature Laboratory. This particular electrode has had extensive use in low current steady state arcs with the conclusion that the arc should attach and remain at the tip. It was installed with an anode-cathode gap of slightly greater than . ⁻m, the maximum that would break down.

A lamp, mounted behind the cathode on a plexiglas bracket, was used to allign the spectrometer (Fig. 14). The solid cathode first used had this lamp mount installed. The result for a 10,000 amp, 100 microsecond arc on the anode surface was a deep crater surrounded by a radial pattern of solidified copper which had been blown from the crater and an extremely dark deposit. There was, however, no copper vapor evident in the arc. The only possible conclusion is that the copper liquid was being blown away, probably by the cathode jet, as soon as it was formed and the surface never reached the vaporization temperature.

In order to allign the spectrometer to more specific parts of the arc, the allignment light was removed and the spectrometer was alligned with a laser. With no changes to the arc configuration other than the removal of the plexiglas mount (Fig. 14), the anode

22

exhibited no erosion but only a large discolored area (Fig. 21-2) much the same as seen for the cathode with the coaxial sparker (Fig. 12 and 21-6).

It seemed obvious that the arc must be climbing the cathode so as to induce motion of the anode attachment area as described for the coaxial sparker cathode but that with the plexiglas mount installed this action was stopped. In order to see just how far the arc would climb the cathode, a brass cathode as shown in Fig. 13 was constructed. The arc left quite distinct tracks on this cathode. There were visible tracks as far as 3/8" from the tip. This type of behavior has been observed on newly ground tungsten cathodes in steady arcs so a tungsten cathode was run, in exactly the same physical situation, with a 100 amp steady arc for about two minutes. The arc attached in a normal manner at the cathode tip. When used again in the pulsed application, it climbed the cathode just as before. With the anode above the cathode, the arc climbed down on the cathode, thus eliminating the possibility of convection causing the motion.

The probable explanation for this behavior lies in a self-magnetic field driving the arc up the side of the cathode (Fig. 15). If the arc deviates from the tip slightly, it must have a bend in order to make the transition from the vertical direction of the column to the direction normal to the cathode surface. Because of this bend, the magnetic field of the column is into the paper at the attachment point. Thus, $\overline{J} \times \overline{B}$ is in an upwards direction parallel to the cathode surface. Note that this assumes the current is carried symmetrically in the cathode and that the column size

23

and radius of bend into the cathode are small. The result is a force, roughly proportional to the square of the current, tending to move the cathode attachment point. This explains why, with the same cathode, the arc will stay at the tip for a steady state low current arc but climbs the cathode at an average vertical velocity of at least 10^4 cm/s for a 10,000 amp arc.

Numerous cathode designs have been tried to eliminate the cathode-induced anode attachment motion. Six of the cathode configurations which have been used are shown in Fig. 12, 13, 14, 16, 17, 18. The corresponding anodes are shown in Fig. 21. All anodes in Fig. 21 have been subjected to one 10,000 amp, 100 microsecond arc. Copper vapor was not seen for any of these anode-cathode combinations.

Fig. 21-2 shows the anode associated with the cathode of Fig. 13. The unsymmetry seen is due to a modified anode holder; if the holder had been the same as for the other shots, it would be more nearly symmetric. No erosion is seen, but rather only a discolored area.

Fig. 21-1 shows the anode associated with the cathode of Fig. 14. It shows a grossly melted crater surrounded by a dark radial pattern. Liquid copper is blown in a radial direction.

Fig. 21-5 shows the anode associated with the cathode of Fig. 16. It shows a similar pattern to that of Fig. 21-1 but is more colorful. The blackness of Fig. 21-1 may be attributable to plexiglas which is charred and deposited on the anode. The outer

diameter of the dark area is smaller than Fig. 21-1 which may
be a result of the shield restricting radial velocity of the
expanding gases.

Fig. 21-4 corresponds to the cathode of Fig. 17. This appears
as a grossly melted region of about 0.5 cm diameter surrounded
by a colorful somewhat less melted region. Craters are evident
in both regions, but the radial pattern of melt flow is not seen
as in Fig. 21-1 and 21-5.

Fig. 21-3 corresponds to the cathode of Fig. 18. This shows
a dark center region, with tungsten deposited in the region of
the center, surrounded by a clean cratered region, in turn surrounded
by a radial flow of copper.

Fig. 21-6 corresponds to the cathode of Fig. 12, the same
design as used by the study at General Dynamics. This shows a
pattern similar to that of Fig. 21-2. The size of the center
dark region is somewhat larger relative to the overall size of
the discolored area than for Fig. 21-2.

C. Results

The design of a cathode which will be useful in studying the
anode of a high current arc presents something of a dilemma. If
the cathode attachment is restricted to the tip, the cathode jet
is directed toward the anode which, of course, influences the
results. On the other hand, if the arc emanates from the side
of the cathode, as it moves around it causes the anode attachment
to move.

A cathode design (Fig. 19) is to be tried in an attempt to circumvent these problems. The idea is to make use of the self-magnetic field to drive the attachment into the throat of a hollow cathode. The impact of the cathode jet would then be taken to a great extent by the opposite wall while the region from which the arc emanates at the cathode is restricted to the area of the throat so that the cathode attachment motion should induce a minimum of anode attachment motion. Any impact of hot gas on the anode from thermal expansion should be minimized by allowing the gases to expand upwards. The smaller diameter center electrode may be used to help start the arc in either of two ways; it can be used as a sparker by applying a high voltage between it and the cathode, or it may be connected to the cathode by a resistance so that when the 10,000 volts are applied to the cathode, the gap will break down due to the pointed cathode but when appreciable current begins to flow the arc will transfer to the main cathode. This cathode is presently being constructed.

Two other possibilities exist for eliminating the cathode influence. One is to restrict the cathode attachment to the tip of a pointed cathode and to have a very large gap between the anode and cathode. This, of course, creates problems in starting the arc. This could be done by reconstructing the apparatus so that the first inductor in the Guillemin line is adjacent to the electrode and applying a pulse of 70 → 100 KV of nanosecond duration. Another is to place an orifice below the cathode. If properly sized, it should cause a reverse flow towards the cathode that counteracts the effect of the cathode jet (Fig. 20).

IV. SUMMARY AND CONCLUSIONS

In order to have valid anode measurements, one must be extremely cautious to eliminate the influence of the cathode, both the impingement of the cathode jet on the anode and the motion of the anode attachment area induced by the cathode spot motion.

Without special care in cathode design, either the arc will move rapidly over a large area of the anode surface and yield extremely low heat fluxes; or the cathode jet will impinge on the anode surface which renders the results meaningless.

Several cathode designs have been tried and have given insight into the behavior of this particular arc. Further work with cathode design is expected to result in a cathode with which the undisturbed anode phenomena can be studied.

REFERENCES

[1] Cohen, M. I., "Melting of a Half-Space Subjected to a Constant Heat Input", J. of The Franklin Institute, Vol. 283, No. 4, April, 1967, p. 271.

[2] Hashemi, H. T. and Sliepcevich, C. M., "A Numerical Method for Solving Two-Dimensional Problems of Heat Conduction with Change of Phase", Chemical Engineering Progress Symposium Series, Heat Transfer with Change of Phase, Vol. 63, No. 79, 1967, p. 34.

[3] Hashemi, H. T., Ph.D. Thesis, University of Oklahoma, Norman (1965).

[4] Douglas, Jim, Jr., "A Survey of Numerical Methods for Parabolic Differential Equations", Advances in Computers, Edited by Alt, F. L., Vol. 2, 1961, Academic Press, p. 1.

[5] Hultgren, R., Orr, R. L., Anderson, P. D., and Kelly, K. K., Selected Values of Thermodynamic Properties of Metals and Alloys, John Wiley and Sons, Inc., 1963.

[6] Thermophysical Properties Research Center, Purdue University, Touloukian, Y. S. and Ho, C. Y., Editors, Thermophysical Properties of Matter, Plenum Publishing Corp., 1970.

[7] Smithells, J. C., Metals Reference Book, Fourth Edition, Butterworth, Inc., 1967.

[8] Chou, T. S., "Anode Contraction Mechanism of High Intensity Arcs", Ph.D. Thesis, University of Minnesota, June, 1971.

[9] Carslaw and Jaeger, Conduction of Heat in Solids, Oxford Press, 1959.

[10] Glasoe, G. N. and Lebacqz, J. V., Pulse Generators, Dover Publications, Inc., 1965.

[11] Metzger, G. and Vabre, J. P., Transmission Lines with Pulse Excitation, Academic Press, Inc., 1969.

[12] Wilson, W. R., "High Current Arc Erosion of Electrical Contact Materials", Proceedings for Engineering Seminar on Electrical Contacts, June 25-29, 1956, Pennsylvania State University

[13] Shih, K. T., "Electrode Erosion in High Current Arcs",
      March, 1970, Contract No. F 33615-67-C-1386, Project 7063.

[14] Avseyevich, O. I., "Principles of Erosion During Pulsed
      Discharges", Physical Bases of Electric Spark Machining
      of Materials, Moscow, Izd-vo Nauka, 1966, p. 32-41.

[15] Shih, K. T., "Investigation of Electrode Erosion in High
      Current Electric Arcs", Report for period from March 1
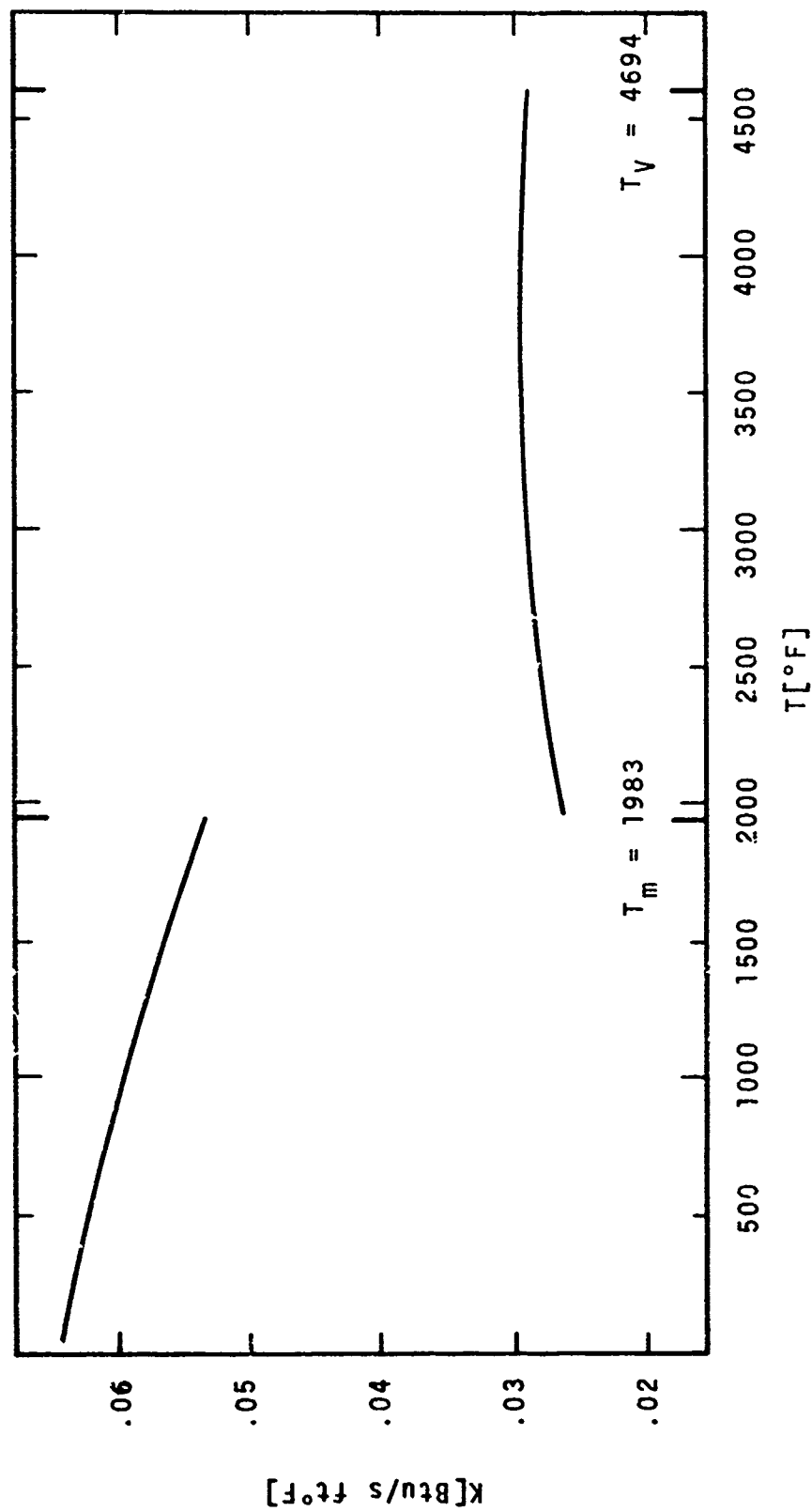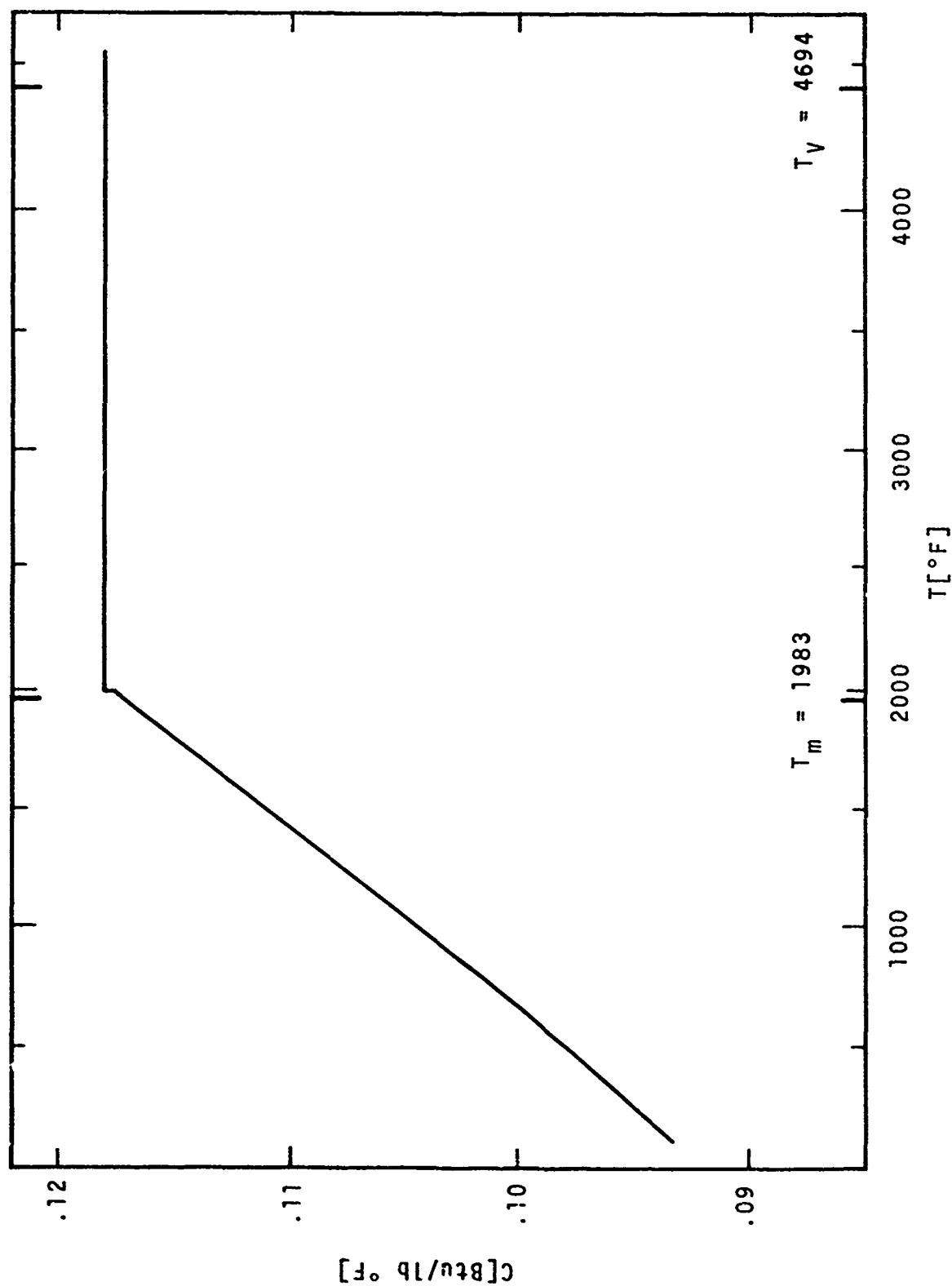   to March 31, 1969, Contract F 33615-67-C-1386.

Fig. 1: Copper Thermal Conductivity

Fig. 2: Specific Heat of Copper

$T_m = 1983$

$T_V = 4694$

$T[°F]$

$c[Btu/lb °F]$
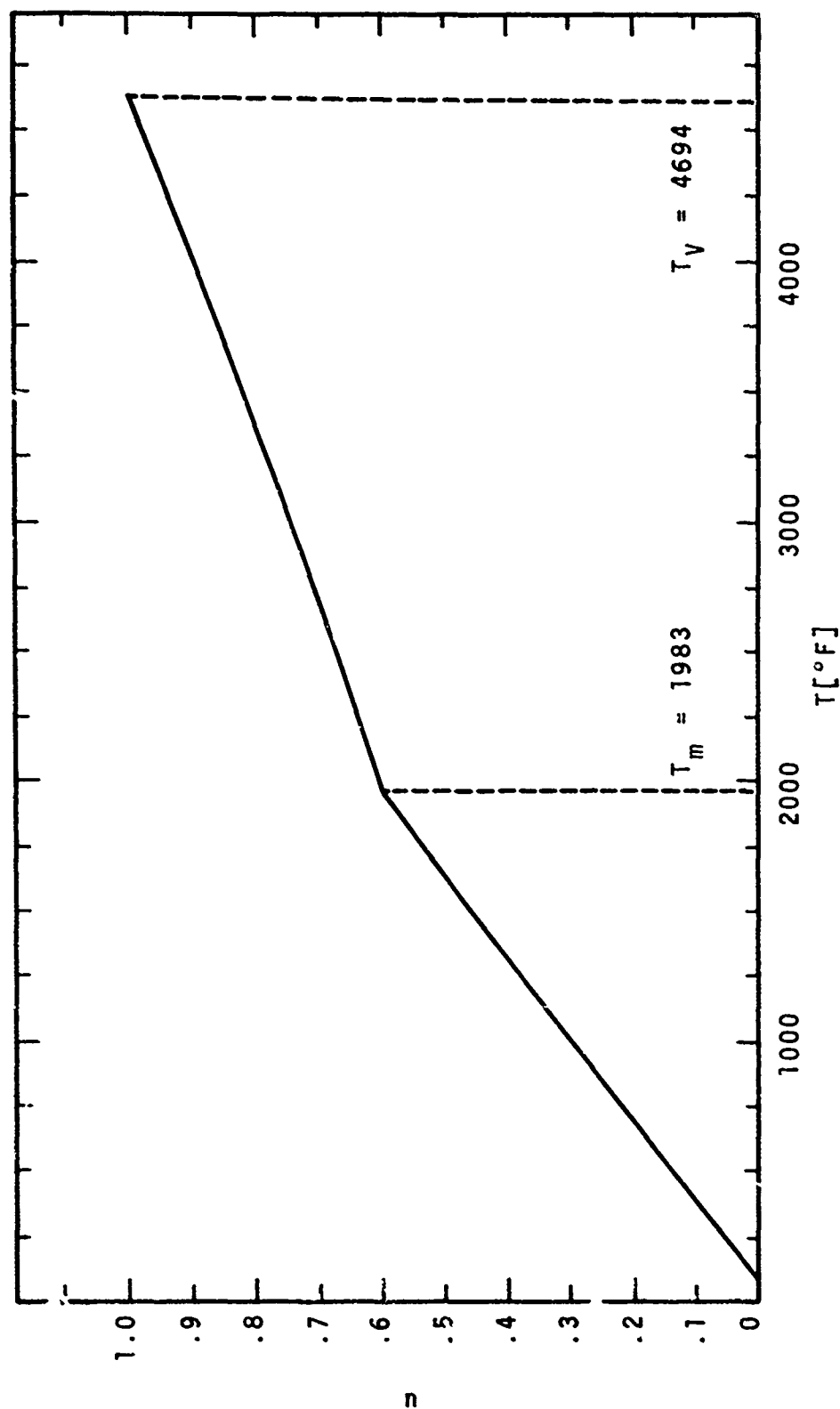
Fig. 3: Dimensionless Temperature (u) for Copper

$T_V = 4694$

$T_m = 1983$
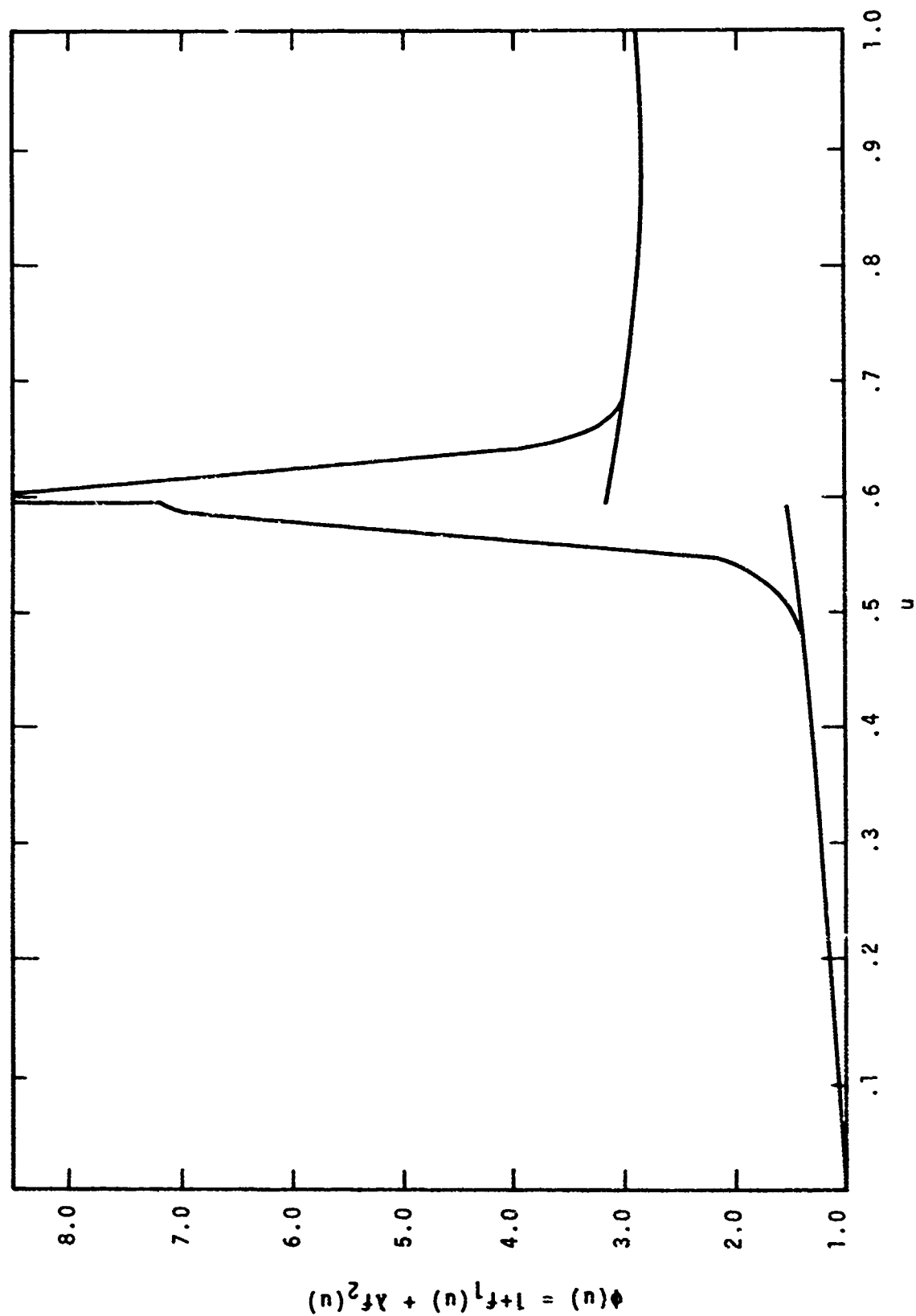
Fig. 4: Copper $\phi(u)$, Function Used in the Solution of Transient Conduction Equation (Eq. 6e)

$\phi(u) = 1 + f_1(u) + \lambda f_2(u)$

33
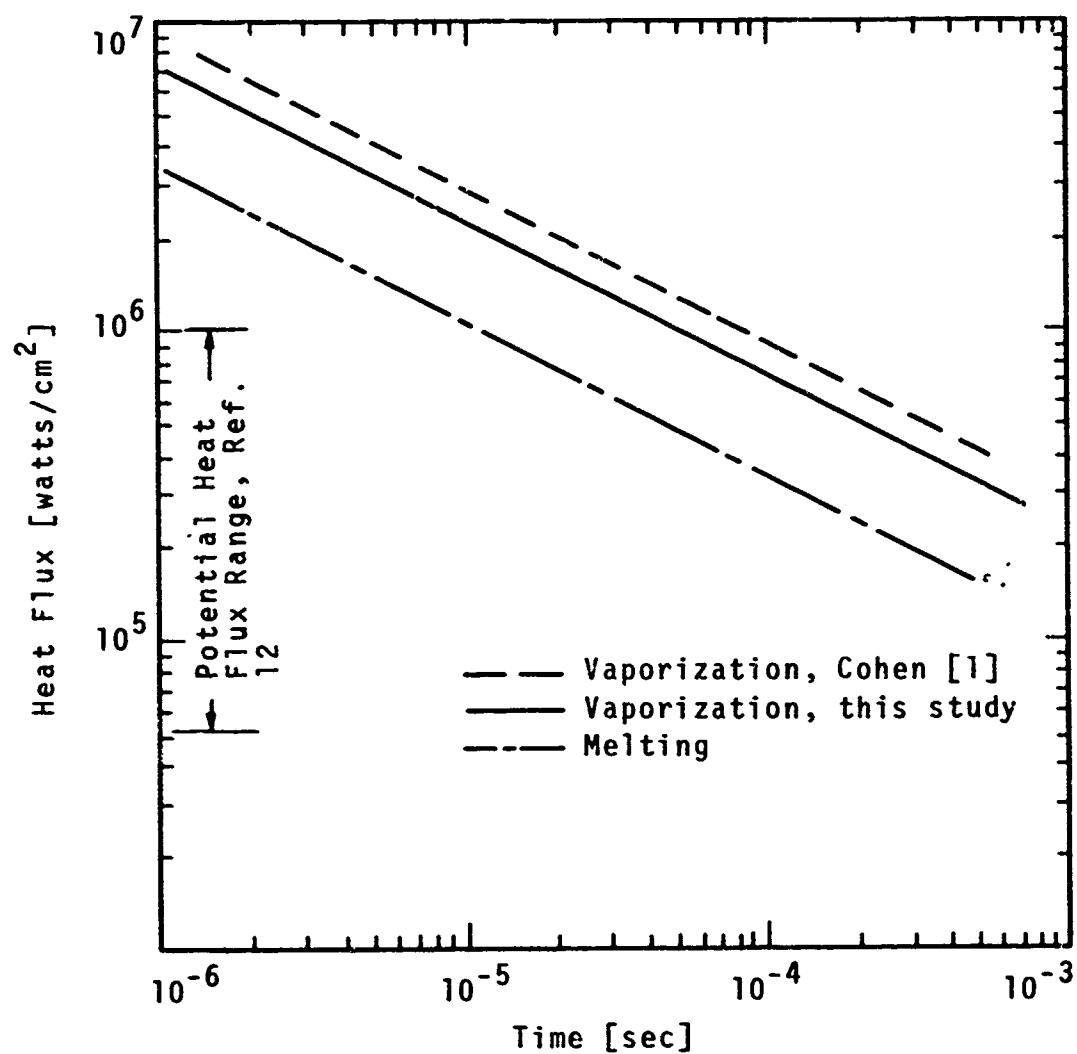
Fig. 5: Time to Melting and
         Vaporization for Copper
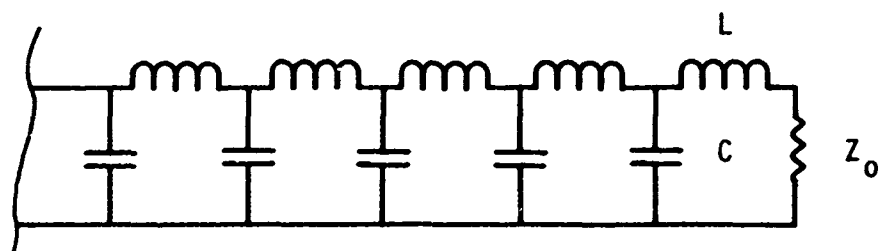
Fig. 6: Guillemin Network

a) $Z_0 = \sqrt{L/C}$ b) $Z_0 = 2 \sqrt{L/C}$ c) $Z_0 = \frac{1}{2} \sqrt{L/C}$
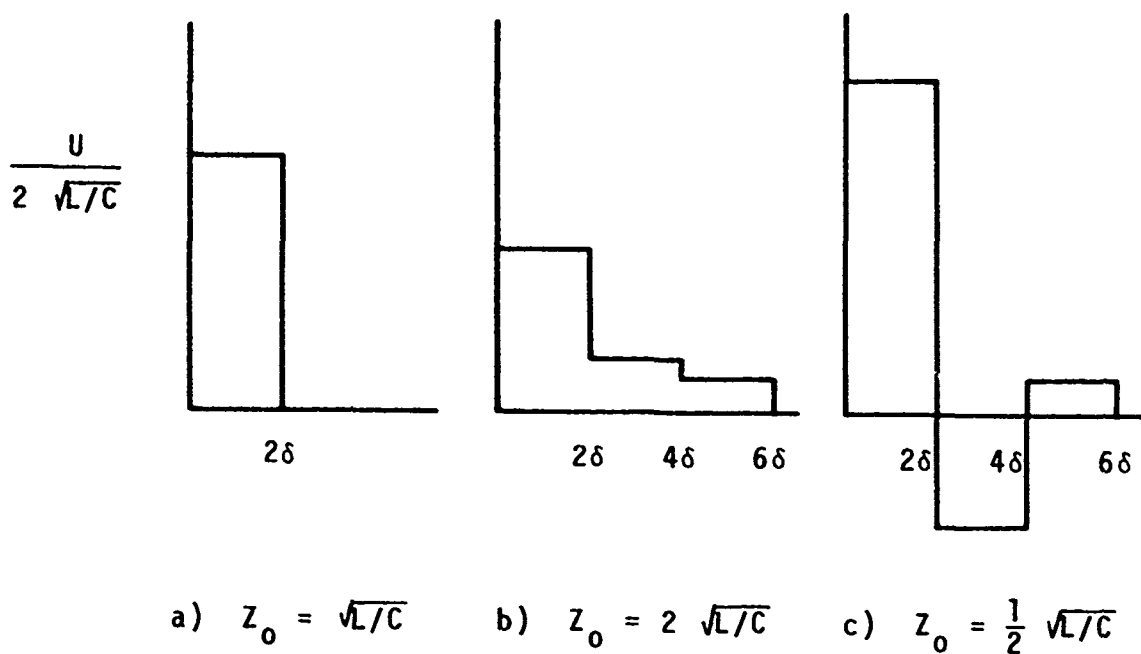
Fig. 7: Current for Guillemin Network
Discharging into Resistive Loads
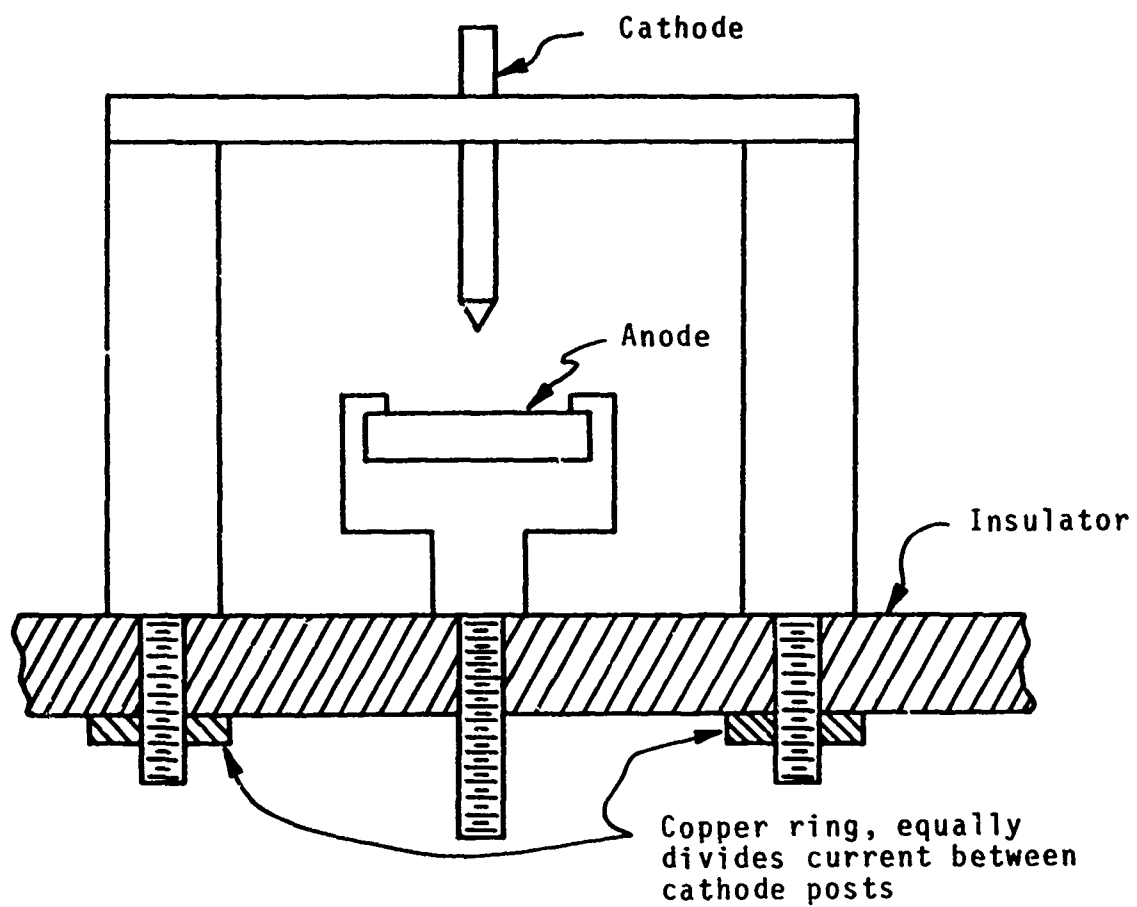
Fig. 8:   Anode-Cathode Mounting
          for Pulsed Arc
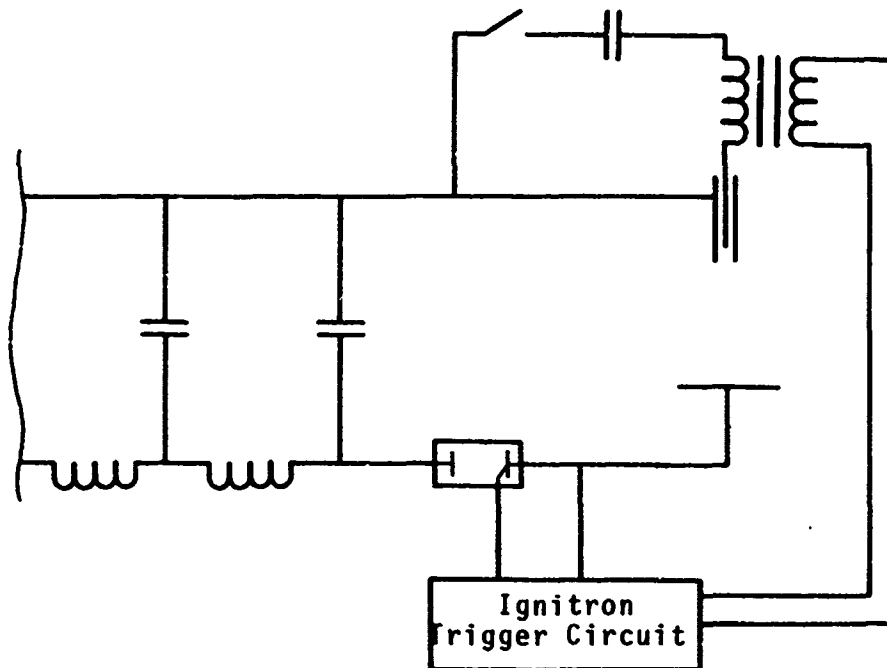
Fig. 9: Circuit with Cathode/Sparker
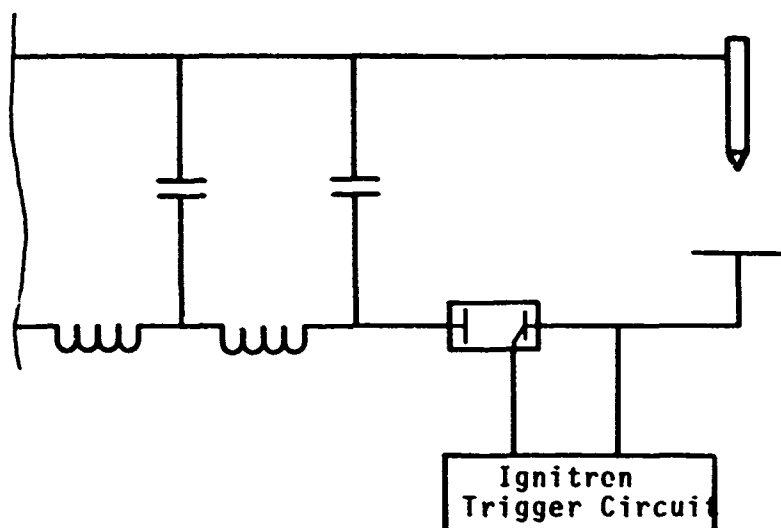
Fig. 10: Circuit with Solid Cathode
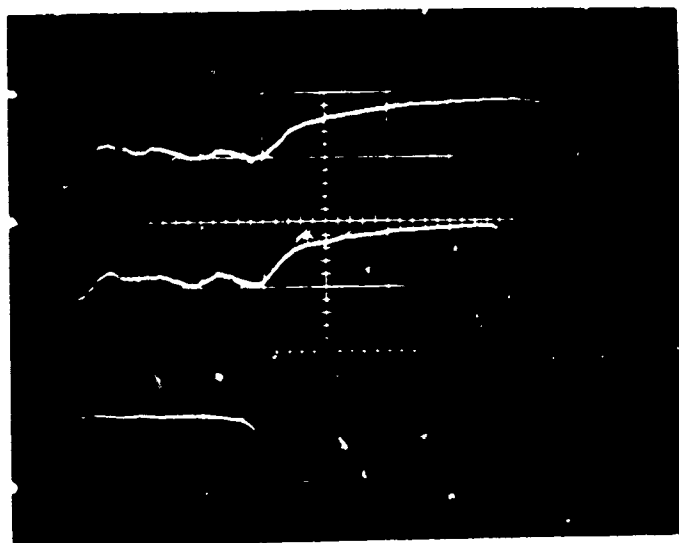
Fig. 11: Current and light emission (5218 Å)
for N_2 arc with copper anode; current
4166 Amp/cm, light relative magnitude
only; second firing shows current
reversal

Fig. 12

Fig. 13

Tungsten Sparker
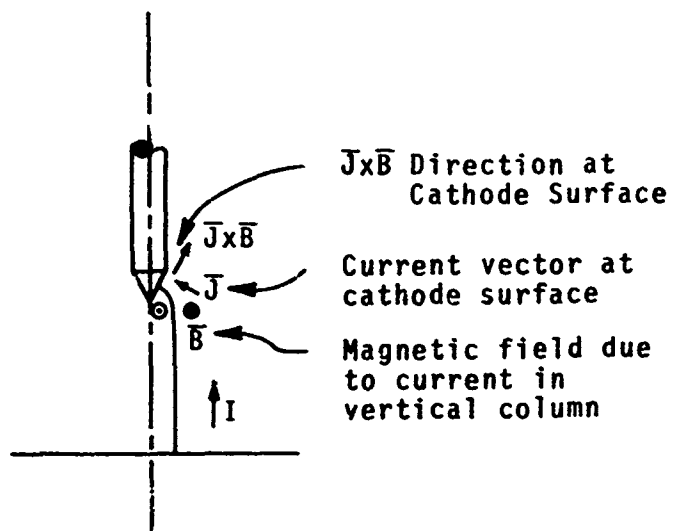
Ceramic Tube

Stainless Steel Tube

Tungsten Tip

Fig. 14

Tungsten Cathode

Plexiglas Mount for Lamp

Fig. 15

$\overline{J}x\overline{B}$ Direction at Cathode Surface

Current vector at cathode surface

Magnetic field due to current in vertical column

Various Cathode Arrangements

Tungsten Cathode

Ceramic Shield

Fig. 16

Brass Cathode Holder

.040-inch
Tungsten Cathode

Lava Shield

Fig. 17

.040-inch
Tungsten Cathode

Brass Cathode
Holder

Lava shield with
.040-inch tungsten
cathode recessed
in .060-inch hole

Fig. 18

.040-inch
Tungsten Rod

Nylon Holder

Brass cathode holder
with vent holes

Lava Shield

Hollow Tungsten Cathode

Fig. 19

Various Cathode Arrangements

Tungsten Cathode
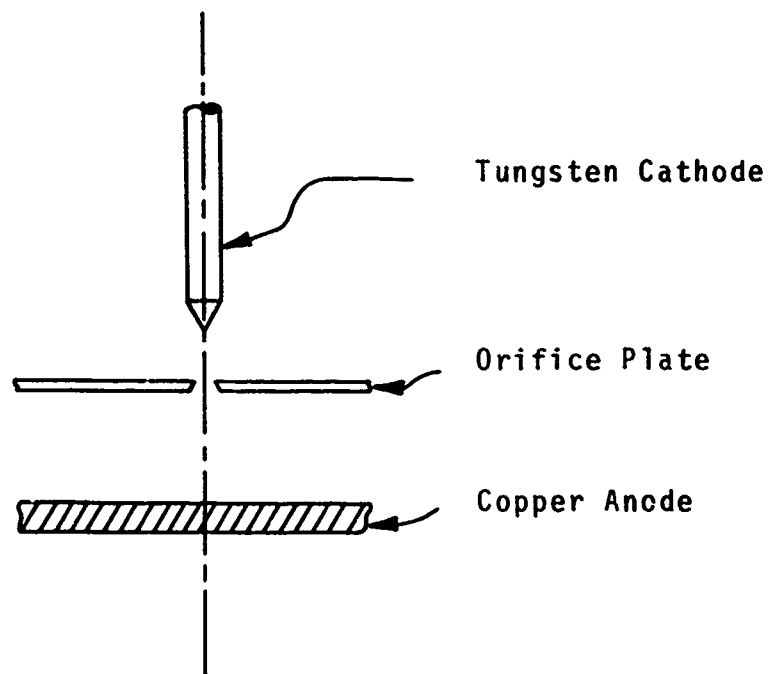
Orifice Plate

Copper Anode
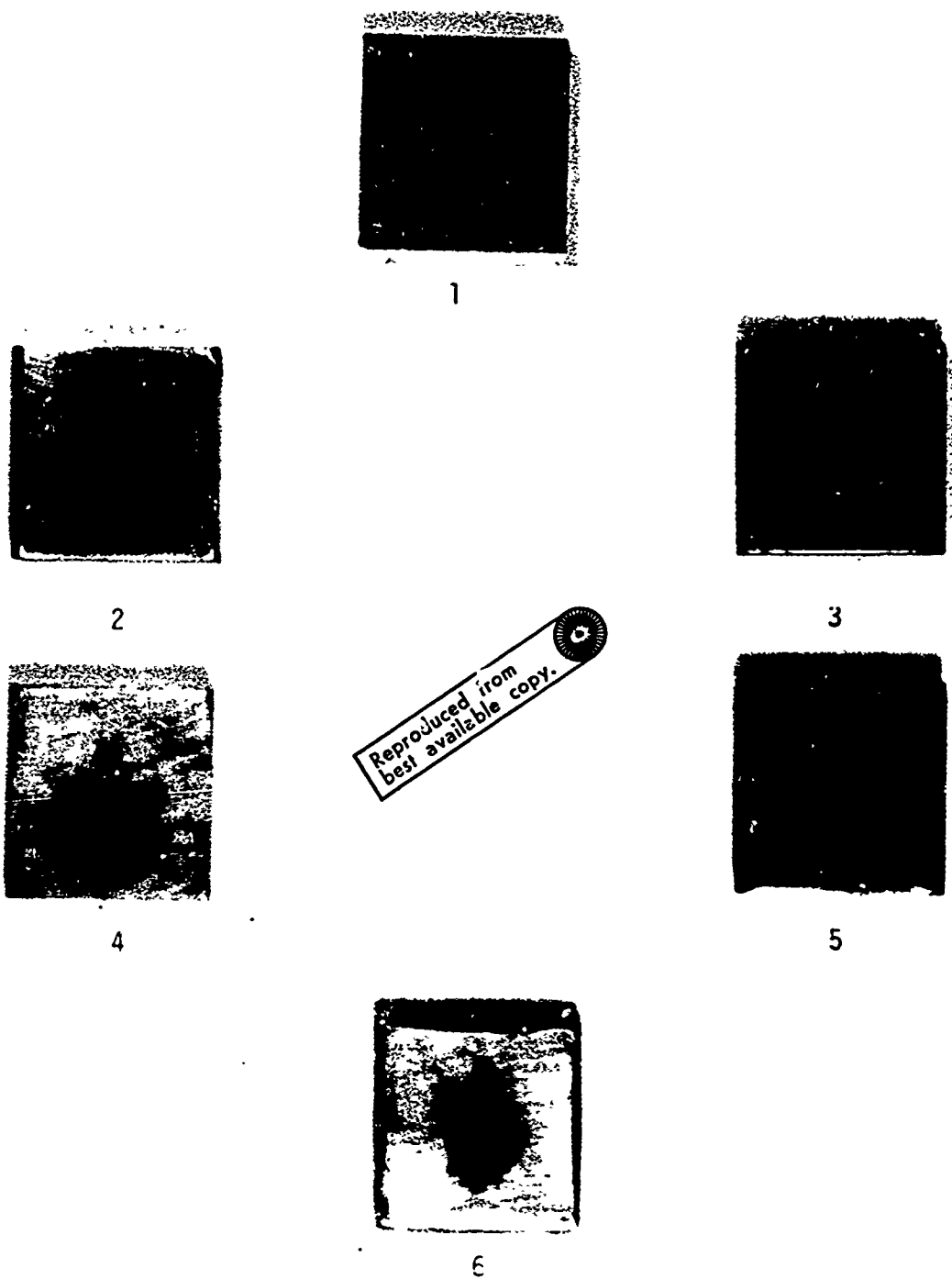
Fig. 20

Cathode Design for Eliminating the Effect
of the Cathode Jet on the Anode

Fig. 21:   Some Typical Anode
42   Erosion Marks